Magnetic draping – from space physics to galaxy clusters and cosmology

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in collaboration with

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Magnetic draping
- Physics
- Solar system
- Galaxy clusters

Spiral galaxies
- Polarized radio ridges
- Draping and synchrotron emission
- Magnetic coherence scale

Implications
- Magnetic field orientations
- Kinetic plasma instabilities
- Cosmological evolution of galaxy clusters
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Draping field lines around a moving object
Draping of solar wind field around the Earth

- the Earth’s dipolar field shields the surface from penetrating cosmic rays

- the magnetic dipole has reversed sign some hundreds of times over the last 400 million years, which may correspond to breakdowns of the dynamo action

- 3D plasma-neutral gas simulations show that the solar wind can induce very fast (∼10 min) a strong magnetic field in the previously completely unmagnetized Earth’s ionosphere

- Earth magnetic polarity reversals may not be catastrophic to life!
Venus and Mars do not have a global magnetic field.

**right:** spatial distribution of the magnetic field strength in the plasma environment surrounding Venus (Venus Express).

Draping of solar wind magnetic field around Venus/Mars leads to the formation of magnetic pile-up region and the magnetotail → enhanced magnetic field strength in the planets’ wake.
Puzzles in galaxy clusters

- radio bubbles, seen as X-ray cavities, are observed out to large distances and have very sharp interfaces: hydrodynamic instabilities should disrupt them

- high-resolution X-ray data reveal ‘cold fronts’ with sharp edges in temperature and density: they are not expected to remain sharp in the presence of diffusion and thermal conduction for $\gtrsim 10^8$ yrs

→ Could bubble/core motions sweep up enough magnetic field to suppress instabilities and diffusion/conduction across the interface?
Idea: magnetic draping comes to rescue (Lyutikov 2004)

- analytics, B-profile along the stagnation line:

\[
\frac{B}{\rho} = \frac{1}{\sqrt{1 - \frac{R^3}{r^3}}} \frac{B_0}{\rho_0}, \quad l_{\text{drape}} \approx \frac{1}{M_A^2} R
\]

- formula predicts infinite B-amplification at the contact that is in conflict with the kinematic assumption of negligible back-reaction

→ need MHD simulations to account for the non-linear feedback!

Lyutikov (2004)
Magnetic draping at radio bubbles

- rising radio bubbles in a hot atmosphere
- shown is the log of the density for the non-draping versus draping case (time increasing upwards)
  - draping suppresses hydrodynamical instabilities in accordance with observations

Ruszkowski et al. (2007)
- dense core of a merging cluster performs sloshing motions in the bottom of the larger clusters’ potential well

- unavoidable draping of a dynamically strong magnetic layer around the contact surface

- draped magnetic field suppresses diffusion/conduction across the interface → sharp density/temperature edges!

Dursi & C.P. (2008)
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Polarized synchrotron emission in a field spiral: M51

- polarized synchrotron intensity follows the spiral pattern and is strongest in between the spiral arms (NGC 6946)
- the polarization ‘B-vectors’ are aligned with the spiral structure
- a promising generating mechanism is the dynamo which transfers mechanical into magnetic energy (Beck et al. 1996)
- efficient dynamo needs turbulent motions and non-uniform (differential) rotation of the disk
Ram-pressure stripping of cluster spirals

- 3D hydrodynamical simulations show that low-density gas in between spiral arms is quickly stripped irrespective of disk radius (Tonnesen & Bryan 2010)
- being flux-frozen into this dilute plasma, the large scale field will also be stripped, leaving behind the small scale field in the star forming regions

→ beam depolarization effects and superposition of causally unconnected star forming patches along the line-of-sight cause the resulting radio synchrotron emission to be effectively unpolarized
Polarized synchrotron ridges in Virgo spirals

Vollmer et al. (2007): 6 cm PI (contours) + B-vectors; Chung et al. (2009): HI (red)
Observational evidence and model challenges

- Asymmetric distributions of polarized intensity at the leading edge with extraplanar emission, sometimes also at the side.
- Coherent alignment of polarization vectors over ≈ 30 kpc.
- Stars lead polarized emission, polarized emission leads gas.
- HI gas only moderately enhanced (factor ≲ 2), localized ‘HI hot spot’ smaller than the polarized emission region:
  
  \[ n_{\text{compr}} \simeq n_{\text{icm}} \frac{v_{\text{gal}}^2}{c_{\text{ism}}^2} \simeq 1 \text{ cm}^{-3} \simeq \langle n_{\text{ism}} \rangle \]

- Flat radio spectral index (similar to the Milky Way) that steepens towards the edges of the polarized ridge.
- No or weak Kelvin-Helmholtz instabilities at interface detectable.

→ Previous models that use ram-pressure compressed galactic magnetic fields fail to explain most of these points!
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- asymmetric distributions of polarized intensity at the leading edge with extraplanar emission, sometimes also at the side
- coherent alignment of polarization vectors over $\sim 30$ kpc
- stars lead polarized emission, polarized emission leads gas
- HI gas only moderately enhanced (factor $\lesssim 2$), localized ‘HI hot spot’ smaller than the polarized emission region:
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$\rightarrow$ need to consider the full MHD of the interaction spiral galaxy and magnetized ICM!
Athena simulations of spiral galaxies interacting with a uniform cluster magnetic field. There is a sheath of strong field draped around the leading edge (field strength is color coded).
the galactic ISM is pushed back by the ram pressure wind $\sim \rho u^2$

the stars are largely unaffected and lead the gas

the draping sheath is formed at the contact of ISM/ICM

as stars become SN, their remnants accelerate CRs that populate the field lines in the draping layer

CRs are transported diffusively (along field lines) and advectively as field lines slip over the galaxy

CRs emit radio synchrotron radiation in the draped region, tracing out the field lines there $\rightarrow$ coherent polarized emission at the galaxies’ leading edges
Magnetic draping and polarized synchrotron emission

Synchrotron B-vectors reflect the upstream orientation of cluster magnetic fields

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Movie of the simulated polarized synchrotron radiation viewed from various angles and with two field orientations.
Streamlines in the rest frame of the galaxy

- as the flow approaches the galaxy it decelerates and gets deflected
- only those streamlines initially in a narrow tube of radius
  \[ \lambda_\perp \approx R/\sqrt{3\beta M^2} \approx R/15 \approx 1.3 \text{ kpc} \]
  from the stagnation line become part of the magnetic draping layer (color coded) → constraints on \( \lambda_B \)

- the streamlines that do not intersect the tube get deflected away from the galaxy, become never part of the drape and eventually get accelerated (Bernoulli effect)

- note the kink feature in some draping-layer field lines due to back reaction as the solution changes from the hydrodynamic potential flow solution to that in the draped layer
Magnetic draping of a non-uniform B-field
(Non-)observation of polarization twist constrains magnetic coherence length

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observed polarised draping emission → field coherence length $\lambda_B$ is at least galaxy-sized

if $\lambda_B \sim 2R_{\text{gal}}$, then the change of orientation of field vectors imprint as a change of the polarisation vectors along the vertical direction of the ridge showing a ‘polarisation-twist’

the reduced speed of the boundary flow means that a small $L_{\text{drape}}$ corresponds to a larger length scale of the unperturbed magnetic field ahead of the galaxy NGC 4501

$$L_{\text{coh}} \sim \eta L_{\text{drape}} v_{\text{gal}} / v_{\text{drape}} = \eta \tau_{\text{syn}} v_{\text{gal}} > 100 \text{ kpc},$$

with $\tau_{\text{syn}} \sim 5 \times 10^7 \text{ yr}$, $v_{\text{gal}} \sim 1000 \text{ km/s}$, and a geometric factor $\eta \sim 2$
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Varying galaxy inclination and magnetic tilt

Side view: Galaxy moving upwards

Top view: Galaxy moving out of page
Observations versus simulations

A
- ram-pressure stripped tail
- HI hot spot
- projected proper motion vector
- projected normal to the PI hot spot

B

C

D

E
- Total PI = 10.41 mJy
- Max PI = 364.4 µJy/beam

F

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Biases in inferring the field orientation

- uncertainties in estimating the 3D velocity: \( v_r \), ram-pressure stripped gas visible in HI morphology \( \rightarrow \hat{\mathbf{v}}_t \)

- direction-of-motion asymmetry: magnetic field components in the direction of motion bias the location of \( B_{\text{max, drape}} \) (figure to the right): draping is absent if \( \mathbf{B} \parallel \mathbf{v}_{\text{gal}} \)

- geometric bias: polarized synchrotron emission only sensitive to traverse magnetic field \( B_t \) (\( \perp \) to LOS) \( \rightarrow \) maximum polarised intensity may bias the location of \( B_{\text{max, drape}} \) towards the location in the drape with large \( B_t \)
Mapping out the magnetic field in Virgo

NGC 4501

NGC 4654

υ < 600 km/s
600 km/s < υ ≤ 1300 km/s
1300 km/s < υ < 2000 km/s
2000 km/s < υ

B

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The alignment of the field in the plane of the sky is significantly more radial than expected from random chance. Considering the sum of deviations from radial alignment gives a chance coincidence of less than 1.7% ($\sim 2.2\sigma$).\(^1\)

For the three nearby galaxy pairs in the data set, all have very similar field orientations.

The isotropic distribution with respect to the centre (M87) is difficult to explain with the past activity of the central AGN.

→ Which effect causes this field geometry?

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\(^1\)Caveat: this statistical analysis does not include systematic uncertainties such as line-of-sight effects.
Magneto-thermal instability: the idea

Convective stability in a gravitational field:

- Classical Schwarzschild criterion: \( \frac{dS}{dz} > 0 \)
- Long MFP, Balbus criterion: \( \frac{dT}{dz} > 0 \)
- New instability causes field lines to reorient radially → efficient thermal conduction radially (close to Spitzer)

The non-linear behavior of the MTI (Parrish & Stone 2007).

- Adiabatic boundary conditions for \( T(r) \): the instability can exhaust the source of free energy → isothermal profile
- Fixed boundary conditions for \( T(r) \): field lines stay preferentially radially aligned (35 deg mean deviation from radial)
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Gravitational shock wave heating

The observed temperature profile in clusters is decreasing outwards which is the necessary condition for MTI to operate → gravitational heating can stabilize the temperature profile:

Mach number distribution weighted by $\varepsilon_{\text{diss}}$.

Energy flux through shock surface $\dot{E}_{\text{diss}}/R^2 \sim \rho v^3$ → increase towards the center.

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radial fields in non-cool core clusters (NCCs) imply efficient thermal conduction that stabilizes these systems against entering a cool-core state: \( \tau_{\text{cond}} = \frac{\lambda^2}{\chi_C} \approx 2.3 \times 10^7 \text{ yr} \ (\lambda/100 \text{ kpc})^2 \), where \( \chi_C \) is the Spitzer thermal diffusivity (using \( kT = 10 \text{ keV} \), \( n = 5 \times 10^{-3} \text{ cm}^{-3} \)).

- current cosmological cluster simulations fail to reproduce NCCs that have no AGN activity → MHD + anisotropic conduction
Speculation: evolutionary sequence of galaxy clusters

After a merging event of a non-cool core cluster, the injected turbulence decays on an eddy turnover time
\[ \tau_{\text{eddy}} \sim \frac{L_{\text{eddy}}}{\nu_{\text{turb}}} \sim \frac{300 \, \text{kpc}}{(300 \, \text{km/s})} \sim 1 \, \text{Gyr}. \]

The magneto-thermal instability grows on a similar timescale of less than 1 Gyr and the magnetic field becomes radially oriented.

The efficient thermal conduction stabilizes this cluster until a cooling instability in the center may cause the cluster to enter a cooling core state – similar to Virgo now – and requires possibly feedback by an active galactic nuclei to be stabilized.
Conclusions on magnetic draping around galaxies

- draping of cluster magnetic fields naturally explains polarization ridges at Virgo spirals

NGC 4501
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- This represents a new tool for measuring the in situ 3D orientation and coherence scale of cluster magnetic fields.
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- Application to the Virgo cluster shows that the magnetic field is preferentially aligned radially.

- This finding is suggestive that the MTI may be operating and implies efficient thermal conduction close to the Spitzer value.
- It also proposes that non-cool core clusters are stabilized by thermal conduction.
Literature for the talk
